CLIMATIC INFLUENCES ON TWO CIÉNEGA COMPLEXES FROM NORTHERN BAJA CALIFORNIA: A ~45,000 YEAR PALEOECOLOGICAL RECORD

by

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A thesis submitted to the faculty of
The University of Utah
in partial fulfillment of the requirements for the degree of

Master of Science

Department of Geography

The University of Utah

May 2016

The University of Utah Graduate School

STATEMENT OF THESIS APPROVAL

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ABSTRACT

Ciénegas are a type of specialized systems that are found in desert landscapes and characterized by organic-rich and waterlogged soils. The existence of these systems corresponds with stability of the hydrologic cycle in arid landscapes so that when they are active they serve as a dependable source of water, as well as provide habitats for many different native plants and organisms. Ciénega Chimeneas and Ciénega San Faustino are desert wetlands located in the Sierra de Juárez of northern Baja California. Today, both sites are ephemerally active ciénegas, but our records indicate that changes in both the timing and amount of precipitation over the last 45 kcal BP have influenced the presence and state of these systems. From ~45-13 kcal BP (during the last glacial period) enhanced winter precipitation supported a landscape that was dominated by chaparral vegetation and increased fire activity at both sites. By ~13 kcal BP, both winter and summer precipitation helped to sustain perennial ciénega complexes and decrease fire activity into the early Holocene. Like many other records throughout southwest North America, we do not have a continuous record of the mid-to-late-Holocene because climate during this time was not conducive to creating an active depositional environment. In this paper, we will discuss how fluctuating moisture sources linked to phenomena such as the modern onset of the El Niño Southern Oscillation and North American Monsoon created enhanced interannual variability that altered sedimentation and productivity at our sites during this time. Our study of ciénega activity in northern Baja California indicate how these systems are sensitive to abrupt changes in precipitation and periods of increased climatic variability. Our findings will provide land managers with critical information about when

and where changes in the seasonality of precipitation have occurred and how changes in the available moisture sources have influenced this region's climate and landscape over the last ~45 kcal BP.

To my father, John Duran, and step-father, Joe Chavez

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ACKNOWLEDGEMENTS

I am forever grateful for the incredible support from my research advisor, Prof. Andrea Brunelle. Her guidance and enthusiasm helped mold me into the scientist I am today and will continue to inspire all of my future endeavors.

I would like to thank my committee members, Dr. Simon Brewer and Dr. Jennifer Watt, for both their time and support throughout my graduate career. I would also like to thank the Department of Geography and the University of Utah for providing me with financial support, as well as the Global Change and Sustainability Center, the Donald Currey Foundation and the EPA SCERP for funding different aspects of my project.

I am grateful to the RED Lab and its members (both past and present) as well as all of its affiliates. I was so fortunate to work with so many kind-hearted, hard-working, and all-around super awesome people. Thank you for making my time at the U unforgettable.

Finally, I am so incredibly thankful to have such a loving and supportive family and group of friends. Grandpa & Grandma, it is because of the unwavering love and support that you provided me with that I have come this far. Mother, I am forever in awe of the courage and selflessness it took to give me the childhood you felt I deserved. Trevor, thank you for being my best friend, partner, and finest fur-dad in all the land. I love you forever and always. Benjamin & Eden, thanks for all your cuddles. I don't know what I would do without you (except for have less fur on all of my clothes).

INTRODUCTION

Since the industrial revolution, global climates have been changing and continue to change at unprecedented rates (Field et al., 2014). Expected changes in our climate system will result in increased variability in the distribution of precipitation, groundwater recharge, surface water availability, and vulnerability to fire (Saunders, Montgomery, & Easley, 2008). In arid and semi-arid regions these changes will likely have significant consequences, not only for human populations occupying them but for ecosystems, flora, and fauna (Ferré, & Leake, eds., 2007; Scanlon et al. 2006; Stonestrom, Constantz). Degradation, which has already resulted in desert landscapes that once supported active and healthy ciénegas becoming largely barren of vegetation and organic soils, as well as extremely susceptible to erosion will likely be intensified by these projected changes (Hendrickson & Minckley, 1984; Minckley & Brown 1982; Minckley & Brunelle, 2007).

Ciénegas provide important ecosystem services in arid regions, such as acting as a dependable water source and promoting vegetation growth. When active, they are characterized by organic-rich and waterlogged soils and form where groundwater tables are highest, which promotes surface inundation (Hendrickson & Minckley, 1985). An active ciénega, therefore, is strongly correlated with stability within the hydrologic cycle in arid landscapes and responds quickly to changes in effective moisture (Minckley & Brunelle, 2007). Furthermore, ciénegas play a critical role in preventing erosion and the formation of arroyos by promoting the growth of vegetation that helps to slow down and absorb water and sediment that runs down from high-energy storms, thus creating an active depositional environment (Minckley & Brunelle, 2007).

The deserts throughout the southwest United States (U.S.) and U.S.-Mexican borderlands (hereafter, southwest North America) are particularly sensitive to the amount and timing of precipitation, which recharges groundwater and helps to maintain a stable ecosystem (Stonestrom, Constantz, Ferré, & Leake, eds., 2007; Waters & Haynes, 2001). Throughout the last few centuries, lowering of groundwater and the water table has caused desiccation of the surface in many desert ecosystems. Since groundwater is largely responsible for the sustainability of ciénegas, the combination of drought, water diversion, and ground water pumping for agriculture has played a major role in the deactivation of these systems throughout southwest North America (Minckley et al., 2011). Additionally, the introduction of non-native plant species, fire suppression, and climate change have also intensified the degradation of desert landscapes and the loss of ciénega soil surfaces (Minckley & Brown 1982; Hendrickson & Minckley, 1984). Much of the research in southwest North America has concentrated on identifying moisture sources via oceanic and atmospheric patterns in order to understand what the dominant climate patterns that drive precipitation have been over time. Since the late Pleistocene, evidence for increased winter and/or summer precipitation is highly variable across spatial scales, which likely affected the presence and state of ciénega complexes on the landscape. As changes in precipitation patterns and the hydrologic cycle are expected to occur in the future (Field et al., 2014), understanding the past relationship between ciénegas and climate can provide land managers with baseline information to use in their ongoing conservation efforts.

Here, we use paleoenvironmental reconstructions to examine two ciénega complexes in an area of Mexico that has not been well researched. Our sites, located in the Sierra de Juárez of Baja California, will expand on the working knowledge of ciénegas across larger spatial and temporal scales, which will help us to understand how ciénega dynamics change throughout time and what mechanisms are driving these changes.

Furthermore, this study represents the only long-term fire reconstruction for the region of northern Baja California, thus providing insight into fire-vegetation-climate relationships over the last 45,000 years (45 kcal BP). The main research objectives of this study are to 1) determine the controls on ciénega activity in northern Baja California and 2) determine whether or not the two ciénegas show evidence for changes in seasonal precipitation regimes over time and if so, determine how these changes in the seasonality of precipitation impact fire activity, ciénega activity, and vegetation.

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REGIONAL SETTING

Site Description

Ciénega Chimeneas (32º 14’ 23” N and 116 º 06’ 15” W (Ciénega Chimeneas)), and Ciénega San Faustino (32° 12’ 30.4” N 116° 09’ 55” W (Ciénega San Faustino)), are located at 1,335 m and 1,285 m of elevation, respectively (Figure 1). Currently, both ciénega surfaces show evidence for ephemeral standing water. Ciénega Chimeneas is a large complex containing taxa such as grass (*Poaceae sp.*), rushes (*Juncus sp.*), and sedges (*Cyperaceae sp.*) surrounded by an outer ring of mature sagebrush (*Artemisia tridentata*) and rabbit-brush (*Ericameria sp.*) (Figure 1). Stands of Jeffrey pine (*Pinus jeffreyi*) and Parry pinyon (*Pinus quadrifolia*) are found on the hillsides immediately surrounding the site complex. This pattern of vegetation typically delineates where the water table is the highest, suggesting that Ciénega Chimeneas is prone to frequent inundation. Similar patterns of vegetation can be seen at Ciénega San Faustino, however, small patches of mature sagebrush existing throughout the complex indicate that this site is not as frequently or homogeneously inundated (Figure 1). Unlike ciénega systems that have been documented along river banks and flood plains of the southwest Unites States, the ciénegas in this study do not appear to have been incised over time. This lack in cutting of sediment suggests that most recently this area has not been as frequently disturbed by high-energy storms that typically form arroyos, and/or the geomorphologic setting is not vulnerable to this type of erosion. It also suggests that the ability of these systems to act as active depositional environments is completely dependent on groundwater recharge. The presence of standing water during our field work at Ciénega Chimeneas suggests th-

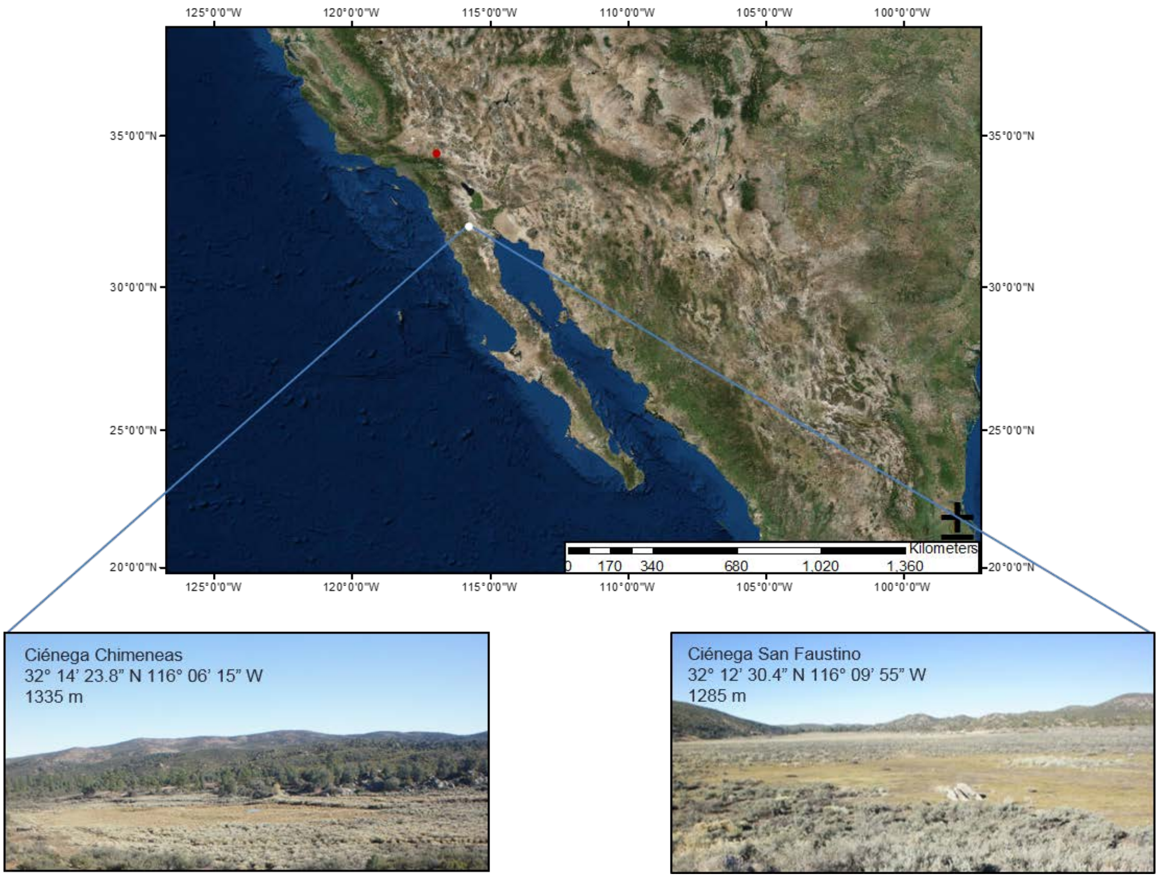

Figure 1. Regional location of Ciénega Chimeneas and Ciénega San Faustino with approximate location of CC12A and CSF12A represented by the white dot. Zoom-ins include the site locations for Ciénega Chimeneas (left) and Ciénega San Faustino (right). The red dot represents the approximate location of Baldwin Lake from Kirby et al. (2006).

at sediment of the uppermost centimeter represents a modern depositional setting, providing us with a unique snapshot into the characteristics of active ciénegas in this region. Therefore, the pollen and charcoal data from this centimeter can be used as a reference to compare against other periods of time where we think the ciénegas were active. The absence of standing water at Ciénega San Faustino at the time these cores were extracted meant we could not include current depositional interpretations of this site.

Our two sites lie within the Mediterranean climate of Baja California encompassing California mountain and chaparral vegetation regimes. The Sierra de Juárez support some of the only forested landscape in Baja California, containing open stands of Parry pinyon and Jeffrey pine (Cartron, Ceballos & Felger, 2005). Common shrubs throughout the California mountain vegetation regime include basin sagebrush, manzanita (*Arctostaphylos pringlei* and *A. pungens*), peninsular oak (*Quercus peninsularis*), and Baja California Rose Sage (*Salvia pachyphylla*). Chaparral vegetation can be found up to 1800 m in this region and is generally a one layered, dense scrub ~1-3 m tall. Common chaparral plants also include sagebrush, as well as chamise (*Adenostoma fasciculatum*), red shank (*Adenostoma sparsifolium*), holly-leaf redberry (*Rhamnus ilicifolia*), as well as a variety of Lilac (*Ceanothus),* buckwheat *(Eriogonum),* and several oak species (Cartron et al., 2005; Rebman & Roberts, 2012).

Geology and Geography

Ciénega Chimeneas and Ciénega San Faustino are located in the Sierra de Juárez, which is the northernmost range in Baja California, Mexico and the southernmost point of the Great Basin Divide. The Sierra de Juárez is part of the north/south trending Peninsular Range, which constitutes the backbone of the Baja peninsula. This range consists primarily of granodiorites and tonalities that formed underneath the earth's crust from ~120-95 million years ago and is derived from the same batholithic chain that formed the ranges seen today from Riverside County, USA (Rebman & Roberts, 2012; Holmgren et al., 2014). Approximately 12.5 million years ago, the Baja California microplate began separating from mainland Mexico, forming the Gulf of California (Fletcher, 2007). This separation helped to establish regional aridity and the unique biogeographic communities throughout Baja California, many of which were reinforced during uplift of the peninsular range that followed the development of the San Andreas fault system, and have persisted to the present (Cartron et al., 2005; Holmgren et al., 2014).

Modern Climate

Climate throughout Baja California, Mexico is quite variable and largely affected by atmospheric and oceanic circulation patterns. The western slope of the Sierra de Juárez, where the study sites are located, receives the majority of its effective moisture during the winter as cyclonic storms travel south via the Pacific storm track and the polar jet stream (Rebman & Roberts, 2012). This west-facing slope creates a moderate rain shadow that blocks Pacific moisture and cool air to the east where the Sonoran Desert is located (Holmgren, 2011). It is estimated that up to 15% of winter precipitation is received as snow above 1,700 m and that the overall amount of precipitation is often amplified during the El Niño phase of the El Niño Southern Oscillation (ENSO), when the trade winds weaken and allow the westerlies to carry more frequent storms to the region (Holmgren et al., 2011; Minnich et al., 2000). To a lesser degree, the North American Monsoon (NAM) system generates precipitation during the summer but commonly yields high evaporation rates, resulting in minimal recharge to the groundwater system. In total, the region receives ~50-70 cm of annual precipitation, 30-40 cm of which falls between December and February (Figure 2) (Minnich et al., 2000). On longer timescales, climate throughout this region is influenced by insolation, oceanic circulation and temperature, continental ice-sheet extent, and various other atmospheric patterns (Kirby et al., 2015; Metcalfe et al., 2015).

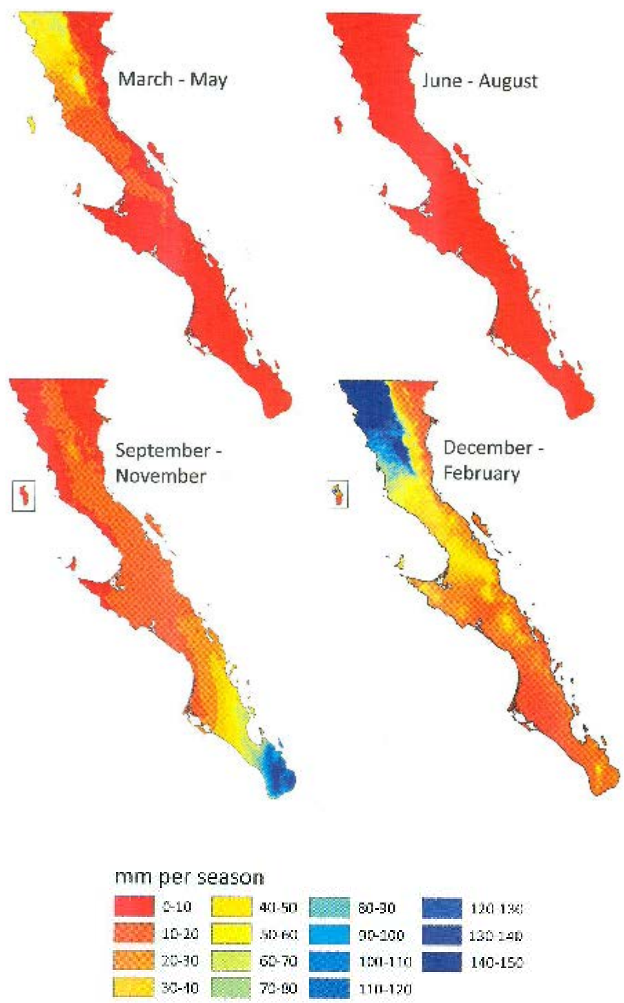

Figure 2. Mean seasonal precipitation for Baja California from Rebman & Roberts (2012). Black dots represent the approximate location of study sites Ciénega Chimeneas and Ciénega San Faustino.

MATERIALS AND METHODS

Field and Lab

Fieldwork was conducted during December 2012. Sediments were collected from two ciénegas, Ciénega Chimeneas (Ciénega Chimeneas) and Ciénega San Faustino (Ciénega San Faustino). These locations were chosen based on vegetation patterns, distance from surrounding granitic rock, and (at Ciénega Chimeneas) the presence of standing water. Vibracoring methods similar to Miller et al. (1991) were utilized by the field crew for this study in an attempt to counter stiff sediments typical of desert wetland environments. Recovery yielded 2.65 m of sediment at Ciénega Chimeneas, and 1.08 m at Ciénega San Faustino. After extraction, the cores were transported to the University of Utah Records of Environment and Disturbance (RED) Lab and stored in a cooler at ~1° C. Both aluminum tubes were cut in half using a circular saw, leaving the sediment core complete and intact. The core lithology was described and recorded for grain size and color using the Munsell Soil Color Chart, then subsampled at contiguous 1 cm intervals and placed in whirl-packs to be stored at the RED Lab at ~1° C.

Chronology

A chronology for each core was determined through AMS ^{14}C dating conducted at the Center for Applied Isotopic Studies at the University of Georgia. All dates were converted to calbrated years using the classical age-depth model (CLAM) and a smoothing spline interpolation and extrapolation of calibrated ages (Table 1) (Blaauw, 2010).

Table 1. Radiocarbon dates and c orresponding ages from Ciénega Chimeneas and Ciénega San Faustino. Asterisks indicate radiocarbon dates that were not included in our age-depth models as a result of possible sediment mixing or younger carbon contamination.

Site	UGAMS #	Depth (cm)	Material Dated	Radiocarbon Age	$\delta^{13}C$	Calibrated Age	Modelled Age
CC12A	19452	4-5	Pollen	8,630 ±25	-22.8	9,536-9,632	10,517
CC12A	16236	11-12	Pollen	*23,650 ±65	-21.1	27,600-27,896	13,775
CC12A	13805	18-19	Pollen	16,590 ±40	-22.3	19,841-20,185	16,673
CC12A	17124	67-68	Pollen	18,845 ±50	-21.0	22,500-22,905	23,883
CC12A	17700	108-109	Pollen	23,080 ±50	-21.5	27,217-27,558	27,139
CC12A	17698	149-150	Pollen	25,830 ±60	-21.1	29,690-30,393	29,808
CC12A	17704	204-205	Pollen	28,460 ±80	-19.9	31,929-32,849	35,915
CC12A	17125	224-225	Pollen	39,000 ±180	-20.0	42,539-43,164	42,234
CC12A	13806	262-263	Pollen	40,820 ±200	-20.6	43,875-44,851	45,374
CSF12A	17702	4-5	Pollen	6,180 ±25	-24.4	7,004-7,163	7,229
CSF12A	16237	13-14	Pollen	*5,860 ±25	-21.0	6,637-6,739	11,726
CSF12A	13807	19-20	Pollen	12,560 ±30	-22.9	14,690-15,110	14,454
CSF12A	17699	29-30	Pollen	14,900 ±35	-23.6	17,945-18,271	18,230
CSF12A	17697	49-50	Pollen	19,810 ±50	-23.8	23,636-24,054	23,855
CSF12A	18462	60-61	Pollen	21,944±70	-23.4	25,953-26,369	26,140
CSF12A	18106	79-80	Pollen	*18,080 ±45	-23.1	21,713-22,121	29,108
CSF12A	13808	107-108	Pollen	28,270 ±80	-22.8	31,673-32,577	32,203

Charcoal

Contiguous 5-cubic-centimeter (cc) volume subsamples were taken from each centimeter of the corresponding core. The samples were soaked for at least 24 hours in sodium hexametaphosphate in order to disaggregate the sediment and then washed through 125 and 250 µm sieves. After sieving, the remaining material was transferred to petri dishes where macroscopic charcoal particles were identified and counted under a dissecting microscope at ~20X magnification.

The total charcoal counts for each core were converted into influx values (particles/cm^2/yr) using sedimentation rates based on the corresponding age-depth model. Background levels of charcoal influx and peak analysis, which represents relatively instantaneous charcoal input or fire events, were identified through Char Analysis (Higuera et al., 2009; Huerta et al., 2009). The background component was determined using a 4,000-yr and 3,000-yr lowess smoother for Ciénega Chimeneas and Ciénega San Faustino, respectively. In order to more accurately compare the trends of fire activity between our two sites and others throughout North America, influx values from each core were normalized using a Box-Cox transformation in R and plotted as standardized values (Power et al., 2008).

Pollen

Pollen was extracted from 1-cc samples following methods developed by Faegri et al. (1989). One *Lycopodium* spore tablet was added to each sample as an exotic tracer. Sampling intervals varied throughout each core in order to establish an approximate 500-1,500 year resolution. A minimum of 300 identifiable terrestrial pollen grains or *Lycopodium* tracers were counted per sample using light microscopy at 500X magnification.

The pollen records for each site are described in terms of percentages of taxa and type of vegetation (i.e., herb, shrub, etc.) and overall pollen accumulation rates (PAR) or pollen influx (grains/cm^2/yr). A combination of visual analysis and stratigraphically constrained cluster analysis (CONISS) (Grimm, 1987) identified significant changes in vegetation regimes, which will be represented by five zones. It has been proposed that the preservation of pollen in sediments is an artifact of reworking or environmental conditions during deposition (Walker & Lowe, 1990). Here, we use a ratio that compares the number of *Lycopodium* tracer grains to identified pollen grains in order to examine pollen preservation at each site over time. This ratio was determined using equation 1.1.

(Eq 1.1) $Pollen\ Preservation = \frac{(Lycopodium\ grains - Identified\ pollen\ grains)}{(Lycopodium\ grains + Identified\ pollen\ grains)}$

We infer lower values to correspond with conditions known to preserve pollen (i.e., wet and anoxic), while higher values represent environmental conditions not conducive to preservation (i.e., warm and/or dry and oxidizing), based on Brunelle et al. (2016). Comparing this ratio with other established means of proxy interpretations, such as pollen accumulation rates, will tell us the significance of using this preservation ratio.

RESULTS AND DISCUSSION

Here, we report and discuss the key findings of our paleoecological reconstructions that allow us to address our objectives, which include determining the controls on ciénega activity in northern Baja California and how changes in the seasonality of precipitation have impacted ciénega activity, fire activity, and vegetation throughout our records. We also discuss how our records compare with other regional studies.

Chronology and Sedimentation

Ciénega Chimeneas

It was determined that the ages of the uppermost 4 cm could not be established after running several models that interpolated up to these surface samples. Because of the presence of standing water at the time this sediment core was retrieved, we concluded that this site represented an active depositional environment and that the age of the youngest deposits likely represented recent conditions for this site. For this reason, the top 4 cm were not included in the age-depth model and, therefore, all pollen and charcoal data for this section have been plotted on depth. Eight AMS radiocarbon dates were used to create the age-depth model for the rest of Ciénega Chimeneas (Figure 3). This model indicated a basal age of 45,374 cal BP and top age of 10,517cal BP, with sedimentation rates ranging between 0.002-0.018 cm/yr. There are two periods of time, from ~33-45 kcal BP and ~13-17 kcal BP, where sedimentation was not consistent enough to infer age-depth relationships, these periods have been modeled through using surrounding radio-carbon dates (Table 1). The primary purpose of modelling through these periods as oppo-

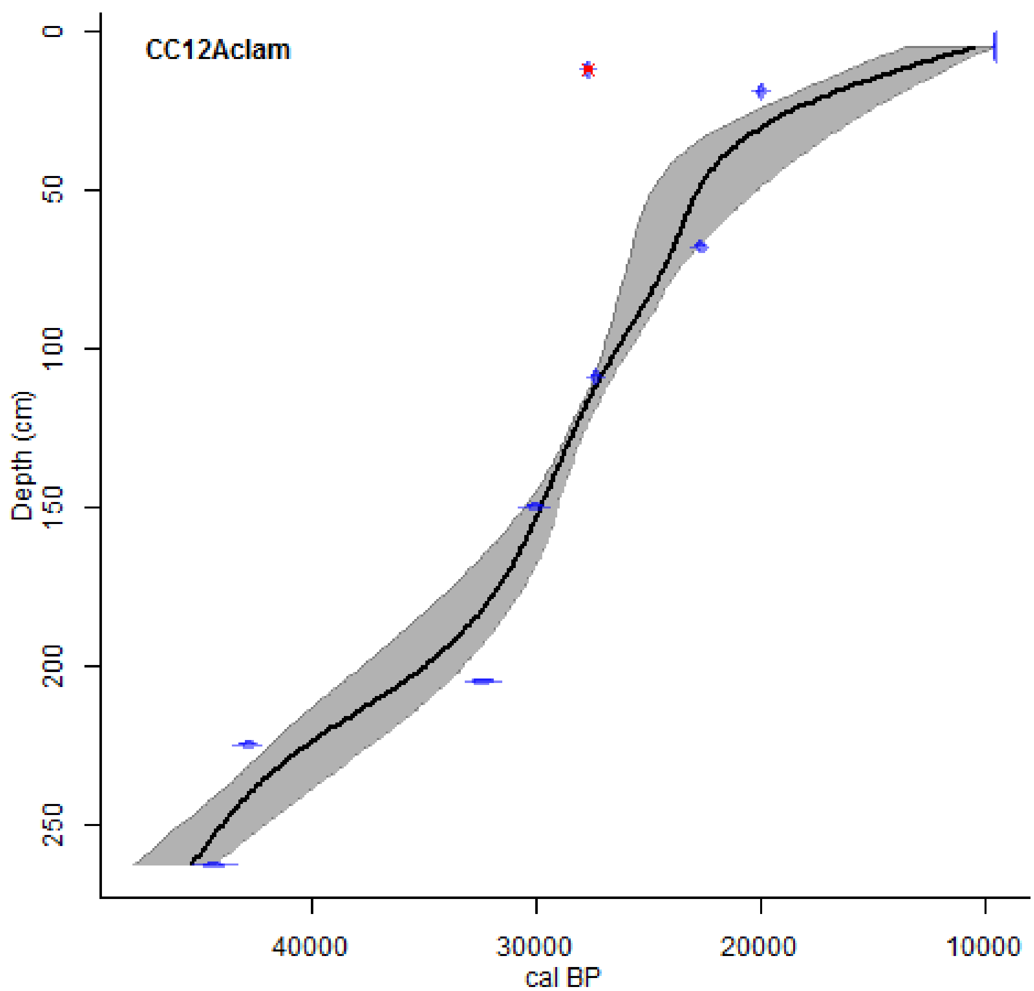

Figure 3. Age-depth model for CC12A. Red X indicates sample left out of model (see Table 1).

sed to breaking our record up by creating multiple age-depth models is to get a sense of the development of this system over time. As a result, the resolution of our record is on the millennial timescale and we do not make any assertions on the exact dates of events but choose to represent our story as one of the evolution of this site over the last ~45 kcal BP. Moreover, any assumptions on the timing of these periods, which are based off of this age-depth model, are consistent with other regional sites throughout southwest North America. Several studies have experienced similar problems with age constraint during at least one of these two periods as well as during the late Holocene (Kirby at al., 2013; Kirby et al., 2006; Lozano-Garcia et al., 2002; Ortega- Guerrero et al., 1999; Roy et al., 2013; Roy et al., 2014). Forcing mechanisms that may be contributing to the apparent inconsistency in sedimentation at these sites, and throughout the region, will be discussed below.

Ciénega San Faustino

Six AMS radiocarbon were used to create the age-depth model for Ciénega San Faustino (Figure 4). This model has an indicated basal age of 32,203 cal BP, top age of 7,229 cal BP. Sedimentation rates vary between 0.002- 0.01 cm/yr and decrease toward the earliest part of the r ecord. Possible carbon contamination and/or inconsistent sedimentation rates resulted in two age reversals; these dates were not included in the final age-depth model (Table 1). Again, we do not make any assertions on the exact dates of events but are representing this reconstruction as an aspect of the evolution of this site. As with Ciénega Chimeneas, the top 4 cm of this core were used to represent more recent conditions, and the corresponding data have been plotted on depth.

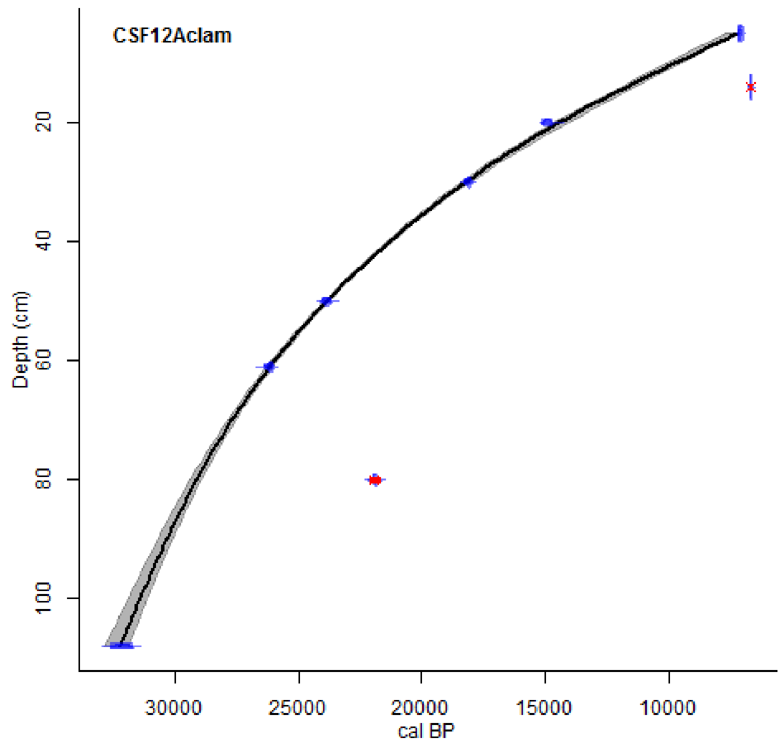

Figure 4. Age-depth model for CSF12A. Red Xs indicate samples left out of model (see Table 1).

Paleoecological Reconstruction

In order to better address the objectives of this study, the paleoecologic record for these sites as reconstructed from the age model will be discussed by separating our data into to five zones: the full glacial, the time period surrounding the last glacial maximum (LGM), the late glacial Holocene transition, the mid-to-late-Holocene, and modern (Table 2). The results and discussion for both sites are included in each of these zones.

Zone 5: The Full Glacial

During the full glacial, vegetation at Ciénega Chimeneas is characterized by shrubs and herbs with minimal to no influence from trees and aquatic taxa, indicating that the landscape was largely dominated by chaparral vegetation at this time and largely in

Table 2. Identified Zones with their corresponding ages and dates for cores CC12A and CSF12A.

Zone	Age (cal BP)	Depth (cm)
5 Full Glacial	CC12A: 45,374- 33,119 CSF12A: NA	CC12A: 263-188 CSF12A: NA
4 The LGM	CC12A: 32,989-13,323 CSF12A: 32,203-13,130	CC12A: 187-11 CSF12A: 108-17
3 Late Glacial Holocene Transition	CC12A: 12,865-10,517 CSF12A: 12,670-7,229	CC12A: 10-5 CSF12A: 16-5
2 Mid to late Holocene	CC12A: NA CSF12A: NA	CC12A: NA CSF12A: NA
1 Modern	CC12A: NA CSF12A: NA	CC12A: 4-1 CSF12A: 4-1

an inactive state (Figure 5). As a result, fire appears to be frequent, but of low severity as indicated by an average influx of ~0.03 particles/cm^2/yr and 3 peaks with an average peak magnitude of 5 particles/cm^2/peak (Figure 5). No other fire records between 20-50° N and 106-120° W exist for this time period, but standardized charcoal influx in the Sierra de Juárez seems to compare more closely with Holocene fire activity in both temperate forest and grassland/dry shrublands (Figure 6). This suggests that fire in northern Baja California during full-glacial conditions acted more similarly to postglacial landscapes throughout western North America. However, slow sedimentation rates and a small sample size throughout this period warrant conservative interpretations of our proxies.

At this time, climate throughout southwest North America was quite variable and influenced by altering moisture sources (Asmerom et al., 2010; Kirby et al., 2006; Roy et al., 2010). For example, Kirby et al. (2006) interpret alternating wet-dry cycles from ~36-49 kcal BP at Baldwin Lake to be a consequence of variability in the frequency of winter storms and the restricted influence of summer precipitation (Figure 1). These conditions

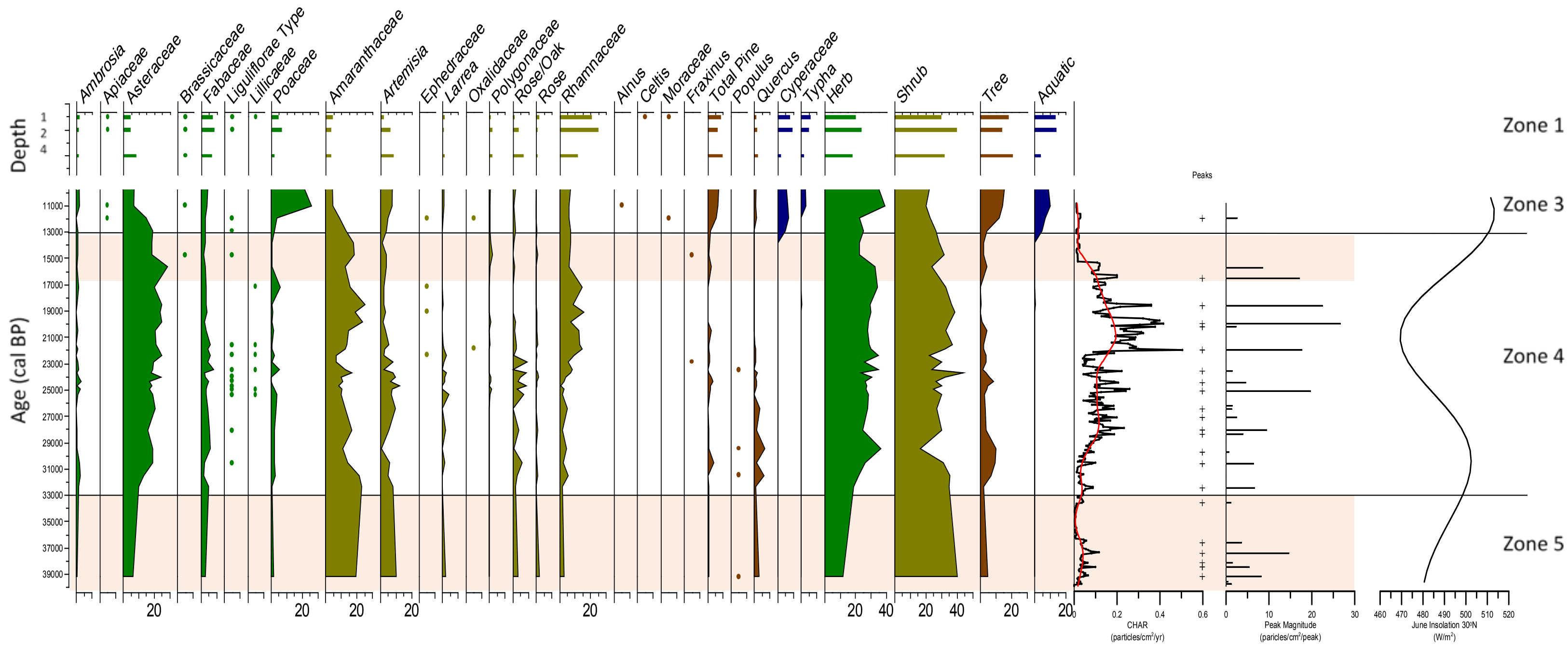

Figure 5. Paleoenvironmental reconstructions for CC12A. Pollen is shown as percentages (sillohuette) or presence (dot). Taxa are split into types according to color, where green=herbs, yellow=shrubs, brown= trees, and blue= aquatics. Fire is shown as influx,with background levels determined by CHAR in red. Fire events, also determined through CHAR analysis, are represented as peaks (+) with the number of charcoal particles per area (peak magnitude) for each peak listed immediately to the right. The summer insolation curve is included for 30°N. Periods of limited age constraint are highlighted in red and the corresponding zone for each section of this record can be found at the far right.

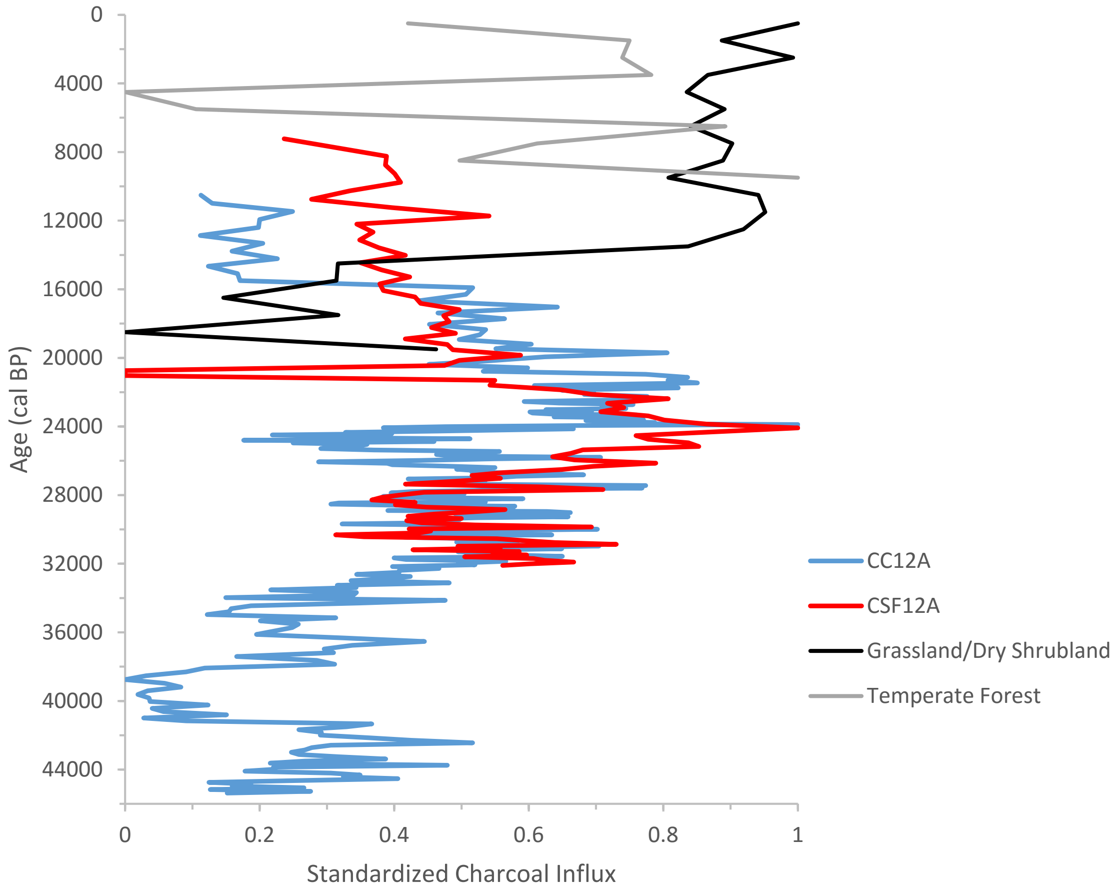

Figure 6. A comparison of standardized charcoal influx values from CC12A, CSF12A, and other fire reconstruction sites found within 20°-50° N and 106°-120° W. Sites are organized by biome according to the Global Charcoal Database (Power et al., 2008), except for CC12A (blue) and CSF12A (red), which are plotted separately.

at Baldwin Lake match increased variability in the GISP2 isotope record and suggest that orbitally driven climate events, such as Heinrich event 4, may be responsible for the extreme wet/dry cycles that were recorded by Kirby et al. (2006). The similarities between Baldwin Lake and the GISP2 records indicate that the eff ects of or bitally driven, high-amplitude climate events were recorded globally. Therefore, we hypothesize that these events also impacted our study sites and could be responsible for inactive ciénega complexes that lead to slow accumulation of sediments during this period lake (Kirby et al., 2006). The similarities between Baldwin Lake and the GISP2 records indicate that the effects of orbitally driven, high-amplitude climate events were recorded globally. Therefore, we hypothesize that these events also impacted our study sites and could be responsible for inactive ciénega complexes that lead to slow accumulation of sediments during this period.

Zone 4: The Last Glacial Maximum

Leading up to, during, and immediately following the LGM, herb and shrub averages for Ciénega Chimeneas were 28.5% and 30.7%, respectively, and 30.4% and 16.7% at Ciénega San Faustino. These percentages are slightly higher, but are still comparable to the rest of the record (Figures 5 & 7). Consistent percentages throughout this period, and across the record, suggest that the chaparral component of these ecosystems is relatively constant over time. Still, the presence of certain taxa provides clues about how this region responded to climatic events such as the LGM. For example, at both sites the highest percentages of sagebrush and varieties from the buckthorn family (*Rhamnaceae*), likely represented by lilac and buckthorn (*Rhamnus*) are recorded during this period. All of these taxa, and others like oak are drought tolerant, which in some cases allows them to go for several weeks without water (Boudreau & Wilson, 1992; Bunting et al., 1987; Hellmers et al., 1955; Hobbs & Wearstler, 1985; Horton, 1949; Tweit & Houston, 1980).

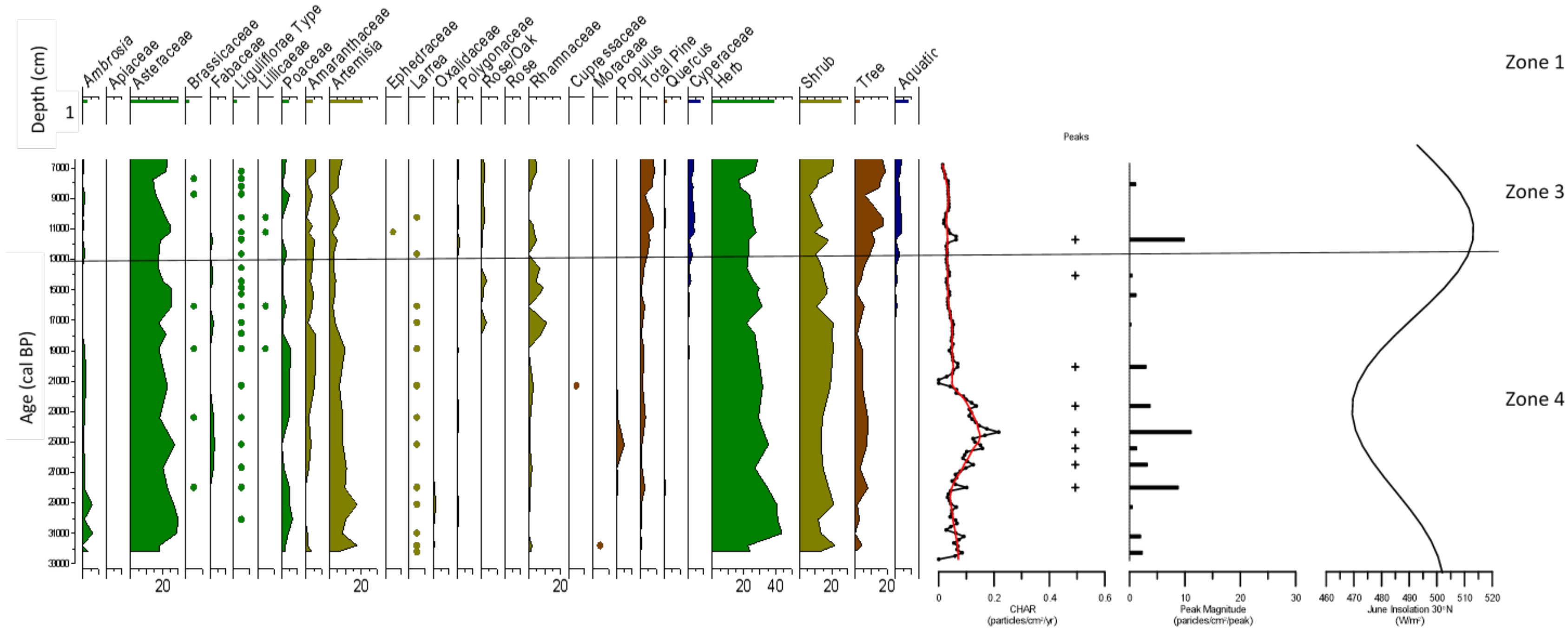

Figure 7. Paleoenvironmental reconstructions for CSF12A. Pollen is shown as percentages (silhouette) or presence (dot). Taxa are split into types according to color, where green=herbs, yellow=shrubs, brown= trees, and blue= aquatics. Fire is shown as influx with background levels determined by CHAR in red. Fire events, also determined through CHAR analysis, are represented as peaks (+) with the number of charcoal particles per area (peak magnitude) for each peak listed immediately to the right. The summer insolation curve is included for 30°N. The corresponding zone for each section of this record can be found at the far right.

The presence of these drought-adapted taxa throughout the pre-and post-LGM period indicates that moisture was likely not available year round, but only seasonally, and that if ciénega complexes were active at any time throughout this period, they were limited to ephemeral activity. Furthermore, the absence of aquatic taxa that depend on a stable water source also supports the idea that the water table may have been quite variable during this time and that these conditions did not allow standing water for the duration needed for aquatic habitat development or preservation. A small peak in cottonwood *(cf. Populus fremontii)* at Ciénega San Faustino around 25 kcal BP further validates the assumption that these ecosystems were being driven by a winter-dominated precipitation regime, since cottonwoods typically thrive under conditions where there is periodic winter flooding and have roots up to 3-5 m in length in order to reach water during summer droughts (Barro et al., 1989; Braatne et al., 1996). Overall, arboreal taxa only made up 3.9% and 3.5% of the vegetation at Ciénega Chimeneas and Ciénega San Faustino, respectively, during the LGM, suggesting that the chaparral component dominated the landscape during this time. Total PAR were highly variable at Ciénega Chimeneas (25-715 grains/cm^2/yr), but were much lower at Ciénega San Faustino (31-145 grains/cm^2/yr). This suggests that, like today, conditions at Ciénega Chimeneas are more prone to inundation, which causes plant productivity around this site to vary more. Pollen preservation mirrors this pattern of variability (or lack thereof) at each site, validating the idea that Ciénega San Faustino was not as frequently inundated during the entirety of the last glacial period and was therefore less productive (Figure 8).

Charcoal influx at both sites shows the greatest number of peaks and highest peak magnitudes during this portion of the record (Figures 5 & 7), indicating that this was a time of pronounced fire activity on the landscape. Leading up to the LGM, between 33,000-24,000 cal BP, charcoal influx at Ciénega Chimeneas averaged 0.11 particles/cm^2/yr. It then increases to ~0.26 particles/cm^2/yr and peak magnitude increased to 17 particles/

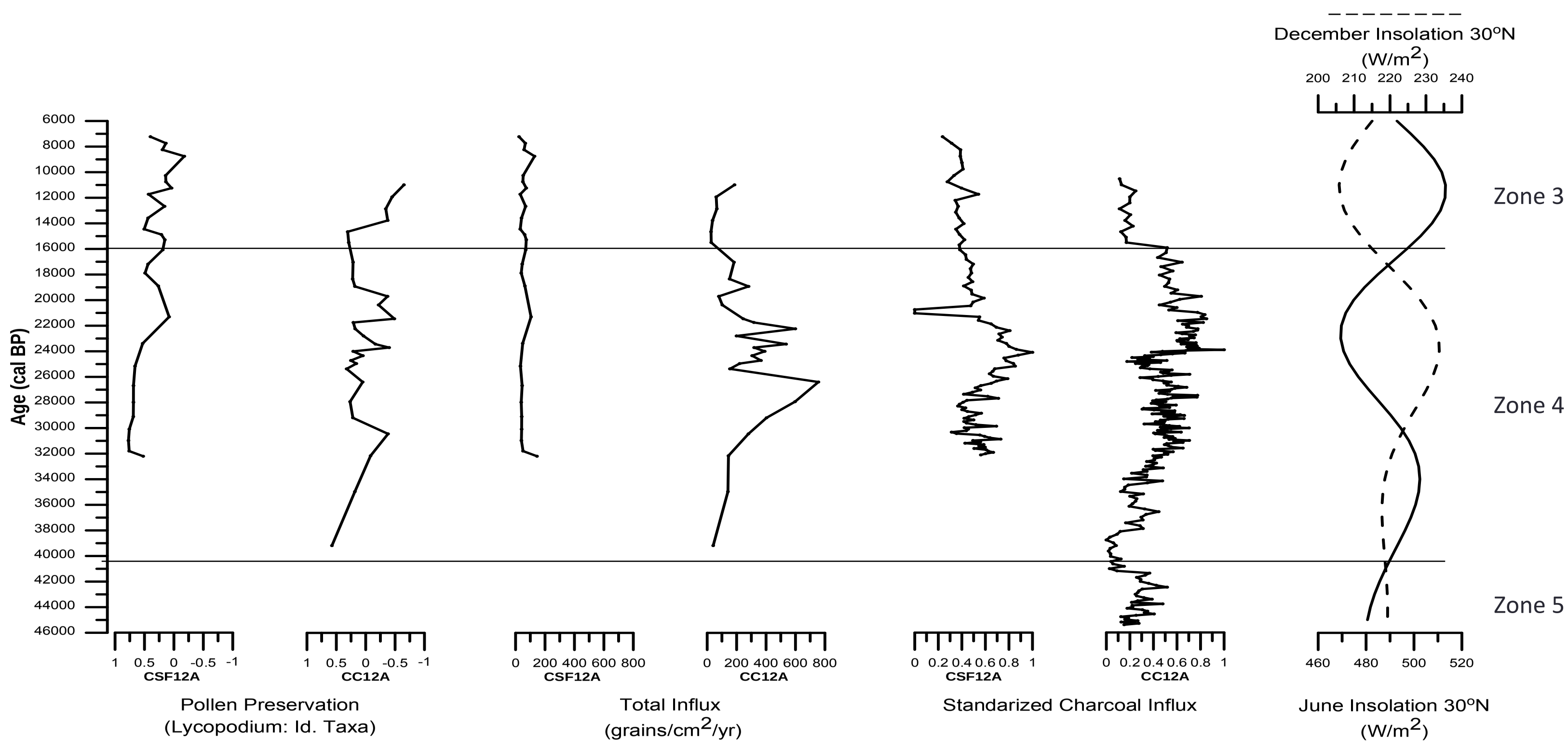

Figure 8. A comparison of pollen preservation, pollen influx, and standardized charcoal influx for each site from ~6 kcal BP to 45 kcal BP. Left panels represent data for CSF12A and right panels represent data for CC12A. Summer (solid line) and winter (dashed line) insolation values for 30°N are plotted farthest to the right. The corresponding zone for each section of this record can be found at the far right.

cm^2/peak compared to the average of 9.4 particles/cm^2/peak between 33-13 kcal BP. At ~19,000 cal BP charcoal influx decreased abruptly to 0.09 particles/cm^2/yr (Figure 5). While Ciénega San Faustino does not have the same distinct step changes as Ciénega Chimeneas, it does show a similar pattern of activity moving from less charcoal (0.06 particles/cm^2/yr) to more charcoal (0.12 particles/cm^2/yr) and then back to less charcoal (0.04 particles/cm^2/yr). Peak magnitude also increased during the LGM at Ciénega San Faustino to 5.4 particles/cm^2/peak compared to the average 3.2 particles/cm^2/peak for this period. Additionally, many of the taxa present on the landscape during this time are either fire adapted or fire dependent. For example, oak, lilac, and buckthorn are fire dependent and readily resprout following low-severity fires (Boudreau & Wilson, 1992; Hellmers et al.1955; Hobbs & Wearstler, 1985; Horton, 1949). Cottonwoods also have the ability to sprout after low-severity fires, but this ability generally decreases with age (Brown et al., 1977), which could explain why their presence at Ciénega San Faustino was so short lived.

Standardized charcoal influx values also show that fire activity at both sites was greatest near the peak of the LGM from ~24-20 kcal BP and that the difference in timing between peak activity for either site is within the errors of dating (Figure 8). Again, there are no other sites from western North America to compare our sites to at this time. However, standardized charcoal influx values suggest that the LGM was a period of greater fire activity compared to glacial and post-glacial conditions in northern Baja California, making it one of the only regions experiencing enhanced fire activity during this time (Danaiu et al., 2009; Power et al., 2008). It is well established that the presence of ice on North America during this time displaced the jet stream to the south, which drove winter storm tracks into the southwestern North America, creating a period of enhanced winter precipitation (Asmerom et al., 2010; COHMAP, 1988; Holmgren et al., 2014; Kutzback, 1987; Thompson & Anderson, 2000). Furthermore, there is a strong relationship of low (high) summer convection with low (high) summer insolation, and other atmospheric patterns such as the southward (northward) displacement of the ITCZ, and a weakened (strengthened) East Pacific Subtropical High (Asmerom et al., 2010; Connin et al., 1998; Kirby et al., 2006; Spaulding & Graumlich, 1986). Therefore, fire is most active at Ciénega Chimeneas and Ciénega San Faustino during periods of enhanced winter precipitation and reduced summer precipitation. Brunelle et al. (2010) demonstrate that fire activity in ciénega complexes increases when there is more winter precipitation. This leads to more spring annual flora that grow as a result of wet winters and are prone to drying out during the summer. As a result, these fine fuels (represented in our records by the large herb component) increase the connectivity of vegetation across the landscape, promoting the likelihood of fire activity. Consequently, fire regimes in these northern Baja California ecosystems seem to be driven by insolation (climate) and the timing of precipitation, while vegetation on the landscape is influenced by the close relationship of climate and fire. This also suggests that the presence of ice in the Northern Hemisphere can influence the landscape in vastly different ways.

Globally, there is evidence that several abrupt climate events occurred as continental ice sheets began to retreat. At Ciénega Chimeneas and Ciénega San Faustino, pollen and charcoal accumulation rates begin to decrease and are lowest at both sites around the timing of the BØlling Allerod (BA), ~15 kcal BP (Figure 8). Again, limited age control between ~13-17 kcal BP suggests we must be cautious in our proxy interpretations during this time. However, there is regional evidence of increased variability in the climate system during the BA and the start of the Younger Dryas (YD) throughout southwest North America (Asmerom et al., 2010; Kirby et al., 2015; Lozano-Garcia et al., 2002; Wagner et al., 2010). Therefore, inconsistent sedimentation rates during this time could be an artifact of regional aridity and/or increased climate variability, which might decrease overall productivity at these sites, causing pollen accumulation and fire activity to also decrease.

This response is similar to that of our sites from 33-45 kcal BP, supporting the idea that Ciénega Chimeneas and Ciénega San Faustino may be sensitive to abrupt shifts in climate.

Zone 3: The Late Glacial-Holocene Transition

During the Late Glacial-Holocene Transition (zone 3), herb sum averaged 27% and 23.5%, and shrub sum averaged 24.3% and 12% at Ciénega Chimeneas and Ciénega San Faustino, respectively. Again, these percentages are comparable to the averages across the record (Figures 5 & 7). In contrast, trees (8.3% and 13.8%) and aquatic averages (5.3% and 3.2%) for Ciénega Chimeneas and Ciénega San Faustino are higher than the previous zones. The percentage of aquatics was comparable to the top centimeter at Ciénega Chimeneas, which represents the modern, active ciénega system. Looking more closely at the components of this zone, we see taxa such as pine and sedges emerging as key plant types. We also see new taxa such as Alder (*cf. Alnus*) and cattail (*Typha sp.*) appearing for the first time. Other notable changes include a peak of 25.7% in grass pollen at ~11 kcal BP, which represents the highest percentage of its type in the entire Ciénega Chimeneas record. The changes in taxa during this period demonstrate their sensitivity to climate fluctuations. In particular, the appearance and regularity of sedges and cattail suggest that standing water may have been available for longer periods of time at both sites since these taxa require saturated or moist habitats (Rebman & Roberts, 2012). Today, several species of pine, oak, and other tree species grow at the perimeter of wet meadows that are common in the Sierra de Juárez (Cartron et al., 2005). It is, therefore, reasonable to conclude that the episodic presence of standing water throughout the late glacial-Holocene transition and early Holocene could create similar meadows or ciénega complexes, which would provide prolonged and superior growing conditions for aquatic plants, as well as certain grasses and trees along the meadow margin.

Plant productivity represented by PAR is lower at Ciénega Chimeneas (35-182 grains/cm^2/yr) than it was during the LGM, but increased toward the early Holocene. PAR rates at Ciénega San Faustino experience the highest value since the LGM at ~9 kcal BP but are otherwise comparable to most of the record (23-128 grains/cm^2/yr). Pollen preservation at both sites generally increased toward the early Holocene, where they reach their highest values (Figure 8). Looking at the fire reconstructions for Ciénega Chimeneas and Ciénega San Faustino, we see that less frequent fire activity on the landscape approaching the early Holocene matches the appearance of water-adapted taxa and increased pollen preservation (Figures 5 & 7), demonstrating that fire activity is primarily controlled by hydrologic changes and the presence of standing water at these ciénega complexes.

After ~13 kcal BP, fire activity is the lowest of the entire record, with mean charcoal influx values of 0.02 and 0.03 particles/cm^2/yr at Ciénega Chimeneas and Ciénega San Faustino, respectively, with only one fire episode for each site at ~12,000 cal BP. This suggests that fires were less frequent in the Sierra de Juárez throughout the late-glacial Holocene transition and into the early Holocene compared to the previous ~32 kcal years (Figure 5 & 7). Standardized charcoal influx values at both sites appear to be more comparable to those from grasslands/dry shrubland sites throughout western North America near the late-glacial Holocene transition (Figure 6). However, there is a general trend of decreasing fire activity in northern Baja California into the Holocene, while fire is becoming more active (higher values) and more intense (amplitude of charcoal influx) in grassland/dry shrubland sites to the north. Consequently, it seems that activity at our sites and those that represent the grassland/dry shrubland biomes of western North America are acting opposite of one another. Climatically, this could be a consequence of the Laurentide ice sheet's retreat across North America during this time, which would have essentially caused a migration of fire at higher latitudes as environmental/climate conditions began to change moving into the Holocene.

Between ~14-12 kcal BP, multiple sites throughout southwest North America show evidence for an onset of increased summer precipitation that persisted into the early-Holocene (Bird & Kirby, 2006; Holmgren et al., 2007; Holmgren et al., 2011; Kirby, 2005; Roy et al., 2014). This timing corresponds well with increasing summer insolation and the northward progression of the jet stream and ITCZ, factors that Metcalfe et al. (2015) suggest play the largest role in the strength of the North American Monsoon (NAM) and its regional extent. As previously stated, fire activity in desert wetland ecosystems has been linked to enhanced winter precipitation (Brunelle et al., 2010). By this time the southern displacement of the jet stream due to ice on North America had begun to wane, but winter precipitation persisted as an important factor in controlling the hydrologic budget (Holmgren et al., 2007; Metcalfe et al., 2015). We hypothesize that reduced winter precipitation (compared to the LGM) and the likelihood of increased summer precipitation may have been enough to reduce fire from the landscape by creating a precipitation regime that delivered effective moisture throughout the year. At our sites, the presence of wet-adapted taxa and decreased fire frequency indicate that this change in the seasonality of precipitation may have helped to sustain perennial ciénega complexes from ~13-7 kcal BP and that, in accordance with the rest of our record, fire activity in the Sierra de Juárez seems to be driven by insolation (climate) and the annual timing of precipitation.

Zone 2: The Mid to Late-Holocene

Unfortunately, there is no continuous record into the mid-to-late Holocene (7.2 kcal BP - present) at our sites. This seems to be a regional issue as many other sites throughout southwest North America experience gaps in their record or difficulty with age-depth relationships during this time (Holmgren et al., 2011; Kirby et al., 2015; Ortega-Guerrero et al., 1999; Roy et al., 2014; Webb & Betancourt, 1990). By the mid-Holocene (5-8 kcal BP) the spatial and temporal availability of both summer and winter precipitation had changed considerably as a result of summer temperatures reaching their maximum, the onset of modern NAM climatology, and the diminished influence of the pacific storm track at lower latitudes (Metcalfe et al., 2015). These conditions seem to have created more variability in fire throughout temperate forests of western North America and increasing fire activity among grasslands/dry shrublands (Figure 6). In northern Baja California and southern California specifically, the mid-Holocene was characterized by increased aridity and aeolian activity (Kirby et al., 2015; Ortega-Guerrero et al., 1999). We hypothesize that during the mid-Holocene our sites experienced overall reduced sedimentation and productivity and therefore were not active depositional environments, which created a gap in our records.

During the mid-Holocene, the climate became increasingly complex as changing moisture sources altered precipitation patterns across North America (Metcalfe et al., 2015). This was likely a result of changes in SST, and less likely a result of summer insolation, as summer insolation was decreasing (Kirby et al., 2015). By ~5 kcal BP, there is evidence for the weakening of the NAM (Metcalfe et al., 2015) and the onset of modern ENSO, which increased the frequency and strength of storms derived from the Pacific (Conroy et al., 2008; Moy et al., 2002). Today we know that Pacific SST, and ENSO in particular, are primary driving mechanisms for precipitation at our sites (Metcalfe et al., 2015; Minnich et al., 2000; Wagner et al., 2010). The Sierra de Juárez experiences wetter than average winters during the El Niño phase of ENSO, and is typically drier than average throughout the year during the La Niña phase (Minnich et al., 2000). Therefore, the diminished influence of summer precipitation via the NAM and the onset of modern ENSO at ~5 kcal BP helped to create a multifaceted pattern of interannual variability throughout this region that has persisted through modern times. The gap in our records from the mid-to-late Holocene indicates once again that these ciénega complexes are sensitive to the timing of precipitation and enhanced variability in the climate system.

Zone 1: Modern

Although we could not provide well-established age control for the top four centimeters of our records, we provide data for this section in order to discuss what more recent conditions looked like at these sites from the depositional record. Overall, the types of taxa in these top samples are consistent with those of the rest of the record. Ciénega Chimeneas has slightly higher averages of shrubs (33%), trees (19%), and aquatics (9.9%), but is lower in herbs (19.9%) (Figure 5). Ciénega San Faustino has higher averages of herbs (39%), shrubs (25.8%), and aquatics (7.8%), but is lower in trees (2.4%) (Figure 7). Consistency of the overall vegetation throughout the entire record, including these top 4 cm, speaks to the overall stability of this landscape over time, even though our records indicate that ciénega complexes in this region are sensitive to abrupt climate events and periods of increased variability within the climate system.

Charcoal concentration values for 1-4 cm vary between 0.6 and 12 particles/cm^3 and 2.4 and 10 particles/cm^3 for Ciénega Chimeneas and Ciénega San Faustino, respectively, with no visible peaks (Figure 9). Since sedimentation rates varied very little from 7-45 kcal BP at either site, we assume that modern sedimentation rates are most likely comparable to those throughout both records. If this assumption is correct, charcoal influx rates would also most likely reflect values similar to 7-13 kcal BP, when fire activity was not a major driving component of landscape dynamics. It has been proposed that fire activity in chaparral and mixed-conifer forests of Baja California is characterized by fine-patch mosaics of low-intensity fires that burn about twice per century (Carton, Ceballos, & Felger, 2005; Minnich, 2001). Although our records do not show evidence of this, it is possible that the apparent lack of fire in the most recent part of our records is not representative of the landscape on larger spatial scales. It is also possible that the lack of fire activity represented in the data from the top 4cm of these cores may be illustrating climatic conditions that are not conducive to fire activity in this region or the effects of human ex-

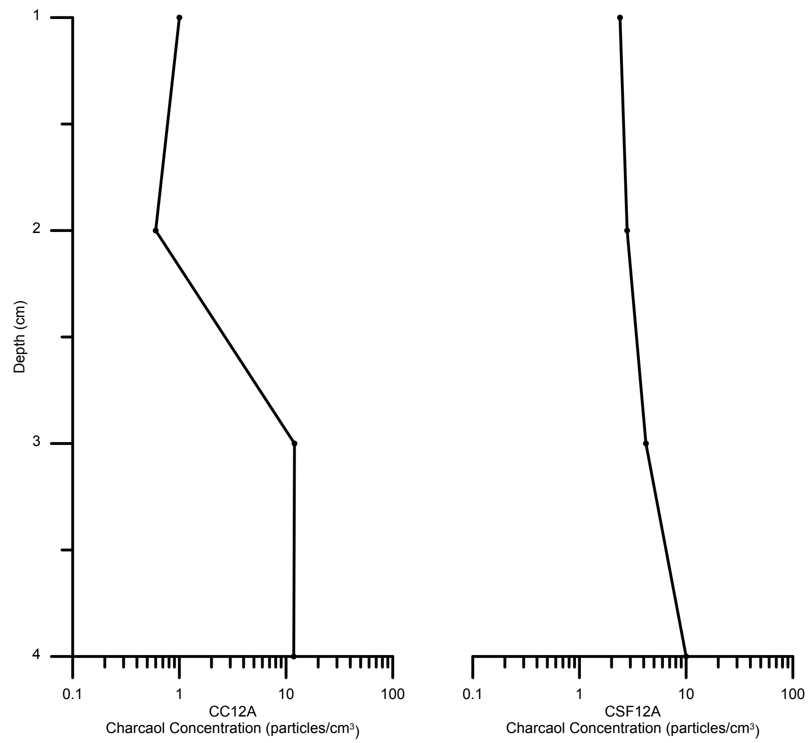

Figure 9. Charcoal concentration values for 1-4 cm at CC12A (left) and CSF12A (right).

ploitation and changes in land-use, such as ranching and cattle grazing, over the last few centuries that have altered the ecosystems of the Sierra de Juárez by removing fine fuels.

The fire reconstructions presented here are the first long-term records of fire variability for northern Baja California, and show that this region has been influenced by millennial scale changes in the hydrologic cycle. We have also illustrated the differences in the timing and intensity of fire activity at our sites compared to temperate forests and grassland/dry shrublands throughout western North America are largely driven by climate. However, since the late-Holocene there has been more interannual-to-decadal fluctuations within the climate system, which would likely impact sedimentation and fire activity. The overall lack of fire research makes it difficult to assign accurate fire regime characteristics for this region. Ultimately, without continuous records that include the last few thousand years, it is hard to provide more specific details on how fire activity dynamics in northern Baja California have evolved with Holocene climate variability, emphasizing the need for continued research.

CONCLUSIONS

In this paper, we present paleoecological reconstructions from Ciénega Chimeneas and Ciénega San Faustino in order to determine the controls on ciénega activity in northern Baja California. Initially, a major goal of this study was to establish whether these ciénega systems showed evidence for a change in the geographic extent and intensity of the NAM during the early Holocene, a hypothesis that was proposed by Barron et al. in 2012 and later by Metcalfe et al. in 2015. Unfortunately, the resolution of this study cannot definitively identify the NAM as the primary source of summer moisture. Instead, we use our reconstructions to look for changes in seasonal precipitation regimes as a result of shifting moisture sources over the last ~45 kcal BP and examine how such changes in the seasonality of precipitation impact ciénega activity, fire activity, and vegetation for the region of northern Baja California.

Our records indicate that since the last glacial period, the activity of ciénega complexes in northern Baja California is largely driven by climate. The influence of insolation on climate during the late-glacial and late-glacial Holocene transition determined when and how much available moisture would reach our sites, thus controlling the hydrologic budget and the ability of ciénegas to act as depositional environments. We hypothesize that the timing of precipitation determines whether our sites are perennial or ephemeral ciénegas, while the total amount of precipitation determines whether or not the complexes can be active at all.

During the late glacial period, climate was characterized by enhanced winter precipitation driven by a displaced jet stream, which created a unimodal precipitation regime throughout southwest North America. These conditions supported the growth of chaparral vegetation communities and promoted more frequent fire activity at our sites. While there is no direct evidence of active ciénega complexes during this time, we cannot definitively rule out their presence. Enhanced winter precipitation created conditions similar to those today where our sites are ephemerally active. Therefore, active ciénega complexes were probably short-lived but most likely present during the last glacial period. As summer insolation increased, ice on North America began to retreat forcing the northward migration of the jet stream and ITCZ, which shifted available moisture sources. By ~13 kcal BP, a shift in vegetation communities and less frequent fire activity at our sites provide evidence for an increase in summer precipitation. These shifts were a result of a bimodal precipitation regime and a positive annual hydrologic budget that supported perennial activity of our ciénega complexes through the early Holocene.

Throughout time, our records show sensitivity to periods of enhanced variability within the climate system, which likely created more frequent and/or intense wet/dry cycles. We attribute periods of inconsistent sedimentation between 45-33 kcal BP and 17-13 kcal BP as well as the gap in our records from ~7 kcal BP- present to increased variability within the climate system that has been documented throughout southwest North America during these times. While ciénega activity has fluctuated over time, the relative uniformity of our pollen reconstructions suggests that dominant terrestrial vegetation at our sites has been quite stable despite large changes within the climate system. This illustrates the ecological capacity of this region to maintain or respond and return to its previous state, in response to disturbances and climatic changes on the landscape. Pollen preservation ratio also records the state of the ciénega over time based on periods of wetting and drying. We saw pollen preservation increase during periods of more available moisture and decrease during dry periods, suggesting that pollen data and specifically the preservation ratio are valuable in recording environmental conditions in arid systems.

We have also provided the first long-term fire reconstruction for northern Baja California, which demonstrates how the seasonality of precipitation has driven the fire regime in this region over long time scales. By comparing fire activity at our sites with temperate forests and grassland/dry shrublands across western Northern America, we saw that the progression of climate from glacial to interglacial played a large role in fire and vegetation regimes throughout time and space. The presence of ice on North America altered the delivery of moisture across the landscape and resulted in a migration of fire activity to the north as the Laurentide Ice Sheet retreated. In our record, this is illustrated by fire activity that peaked during the LGM and decreased toward present. Ultimately, the change reflected at our sites is consistent with the interpretations from other regional records. This suggests that ecosystems throughout southwest North America respond to large-scale changes in the climate system and that these changes have been recorded throughout time. In light of future climate change scenarios, which predict enhanced variability in the distribution of precipitation, groundwater recharge, surface water availability, and increased vulnerability to fire throughout southwest North America, records like those presented in this paper can provide a better understanding on the range of natural variability and responses of the landscape to climate change over time. Future research in this region would benefit from higher resolution reconstructions that cover the early Holocene in order to better understand how landscape responses have evolved with more recent climate fluctuations.

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